A Technology Roadmap for Establishing an Interplanetary Internet

Charles D. Edwards, Jr.
Telecommunications and Mission Operations Directorate
Jet Propulsion Laboratory
M/S 303-402
4800 Oak Grove Drive
Pasadena, CA 91109
chad.edwards@jpl.nasa.gov
http://tmod.jpl.nasa.gov/technology

Abstract

NASA's future mission set calls for significant increases in deep space communications capabilities. Activities such as the intensive exploration of Mars will benefit from and be enabled by breakthrough increases in bandwidth and connectivity. A solar system-wide information architecture, modeled on the Earth's Internet, is envisioned in which information can seamlessly flow from planetary environments back to scientists and the public here on Earth. We present here an overview of some of the key technologies that will play a role in realizing this vision.

Introduction

NASA's strategic plan calls for establishing a virtual presence throughout the solar system. The fidelity of that virtual presence will largely be defined by our capability to move large amounts of information across interplanetary distances. Relative to that goal, today's current deep space communications capabilities represent a severe limitation in planetary exploration. Over the past year, the Telecommunications and Mission Operations Directorate (TMOD) at the Jet Propulsion Laboratory (JPL) has developed a technology roadmap that presents a path to significant growth in NASA's communications bandwidth across the solar system. This paper presents a summary of that roadmap, and describes how it supports the notion of an Interplanetary Internet.

The Internet provides a model for how to embed this communications growth in an evolving architecture that supports information flow across the solar system. While past deep space missions traditionally represented single point-to-point links between a planetary spacecraft and Earth, the future calls for more complex network topologies, with *in situ* exploration involving landers and rovers communicating through networks of relay satellites. We envision an Interplanetary Internet that extends the paradigm of the Earth's Internet to the solar system. Key aspects of this Interplanetary Internet include:

- breakthrough increases in communications bandwidth and connectivity
- IP-like protocols, tailored to operate over the long round-trip light times of interplanetary links
- a layered architecture to support evolvability and interoperability
- seamless end-to-end information flow between science and exploration assets around the solar system and researchers and the public here on Earth
- integration of navigation functionality to extract position information from the communications links.

Key Technologies

Ka-band Ground Systems

As a first step towards increasing the agency's deep space communications capacity, NASA's Deep Space Network (DSN) is initiating the implementation of Ka-band (32 GHz) reception capabilities on all of its ground assets. Current deep space missions typically transmit their telemetry at X-band (8.4 GHz). Moving to the higher Ka-band frequency allows future spacecraft to focus their transmitted power in a more narrow beam, for a given antenna size, thereby increasing communications performance. After accounting for the increased effects of the atmosphere at Ka-band, and the lower efficiency of some of the transmit and receive elements, we expect an overall increase of roughly 6 dB, by moving from X-band to Ka-band.

Several technologies are key to allowing the DSN's large antennas to operate effectively at the short sub-cm wavelength of Ka-band. As these large apertures tip in elevation angle, gravity can cause deformations in the primary antenna surface leading to a loss in efficiency. The DSN's new 34m Beam WaveGuide (BWG) antennas (Figure 1) were specifically designed with stiff structures to minimize these deformations, and they provide excellent aperture efficiency (50-60%) over the full range of elevation angles. The older 70m antennas, however, suffer very large gravity-induced deformations that, if left uncorrected, would preclude their use at Ka-band. We are investigating two techniques for compensating these deformations and obtaining high aperture efficiency on the 70m antennas (Figure 2). The first technique, called a Deformable Flat Plate, places a small reflector with 21 actuators distributed across its face in front of the Ka-band feed. The actuators are programmed to deform this mirror, as a function of elevation angle, to exactly compensate for the predicted gravity-induced deformations of the large 70m primary dish. The second technique, called an Array Feed, surrounds a central Ka-band feed with six additional feeds in a hexagonal pattern. These outer feeds capture the energy in the defocused beam caused by the primary antenna deformation. Real-time signal processing determines the relative phase and amplitude of the signal in each feed element. Based on these complex weights, the seven feed signals are recombined in an adaptive way to compensate for the gravity distortion. Both of these systems are currently being tested on the Goldstone 70m antenna, in order to quantity potential future 70m Ka-band performance and determined the optimal implementation approach.

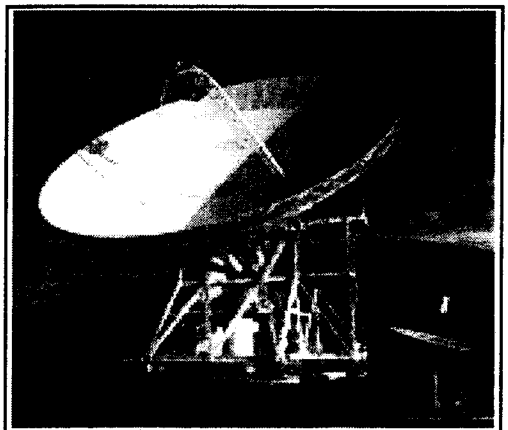

Figure 1: DSS 13, the DSN's 34m Research and Development Antenna

Figure 2: Deformable mirror (left) and seven-element array feed (right), two candidate technologies for achieving high aperture efficiency at 32 GHz on the DSN's 70m antennas.

Accurate pointing is another challenge of operating at Ka-band, since the antenna beamwidth is four times smaller than at X-band. A new feed has been developed that provides X-band transmit and receive capability, along with a tracking Ka-band receive capability, all in a single aperture. This feed can provide closed-loop Ka-band antenna pointing to better than a millidegree of accuracy. This feed can be used by itself on a 34m antenna, or can be combined with the Deformable Flat Plate on the 70m to provide gravity compensation and closed-loop pointing. The Array Feed system, on the other hand, intrinsically provides pointing information in addition to gravity compensation based on the spatial distribution of energy across its seven array elements.

A final key technology for Ka-band ground systems are the low-noise amplifiers that provide high-sensitivity signal reception. JPL has partnered with TRW and Georgia Institute of Technology to develop cryogenic Indium Phosphide (InP) High Electron Mobility Transistor (HEMT) low-noise amplifiers with module noise temperatures of less than 10 K. Based on these technologies, we expect to obtain aperture efficiencies and total system operating temperatures (at 30 deg elevation and 90% weather) of 53% and 71K on our 34m BWG antennas and 36% and 71K on our 70m antennas.

Spacecraft Radio Systems

New spacecraft radio system elements are required to enable future Ka-band missions. Key drivers on these elements are low mass and power, high efficiency and high EIRP, and low cost. At the heart of the future radio system is the Spacecraft Transponding Modem (STM). The STM provides X-band receiver and X/Ka-band exciter functions, supports new high-performance turbo codes, presents a simple frame-level interface to the flight computer, and provides timing and frequency references for the entire spacecraft, all in a 0.9-kg package that comsumes less that 11 W. A full prototype of the STM is currently under development, with completion targeted for 2000.

A critical need for effective use of Ka-band is high-efficiency spacecraft power amplifiers. Current solid-state amplifiers are limited by very low output power and efficiency; for example, the Ka-band SSPA on the New Millennium DS1 mission provides about 2.5 W of RF power with only about 15% efficiency. To address this need, we have recently initiated the development of a Ka-band Travelling Wave Tube Amplifier (TWTA). Goals for this TWTA are output power of 15-30 W and efficiency of >40%.

Finally, a variety of novel spacecraft antenna technologies are being investigated. Several years ago, a 0.5-meter Ka-band reflectarray antenna was built at JPL. In this antenna, a flat surface is covered with passive phase shifting elements, designed so that when illuminated by a Ka-band primary feed, the flat surface behaves like a parabola. More recently, the reflectarray technique is being combined with inflatable structure technologies to build larger Ka-band apertures with very low areal density. The combination of inflatables with reflectarrays is particularly attractive as the reflectarray elements can be placed on a thin, flat sheet which simply needs to be stretched taut by an inflatable torus around its circumference.

Optical Communications

Moving beyond Ka-band, communications at optical wavelengths offers even further opportunities for performance improvements, again based on the higher directivity of the spacecraft signal as wavelength decreases. For instance, a diffraction limited 2-meter Ka-band antenna transmits its signal with a beamwidth of about 5 millirad. By contrast, an optical (1064 nanometer) spacecraft laser transmitted through a much smaller 30 cm diffraction-limited telescope has a beamwidth of just 3.5 microradians.

Important steps have already been taken in the development of space optical communications capability. Several years ago, TMOD and the Japanese Communications Research Laboratory conducted the first bi-directional space-ground optical communications using NASDA's ETS-VI spacecraft and existing telescopes at JPL's Table Mountain Facility (Figure 3). Currently, JPL is developing small, lightweight spacecraft optical transceivers for use in future missions. In concert with these developments, TMOD has initiated the development of a 1-meter Optical Communications Telescope Laboratory (OCTL), sited at JPL's Table Mountain Facility in southern California. This facility will support early earth-orbiting demonstrations of space-to-ground optical communications, such as the planned ISSERT demonstration on the International Space Station, scheduled for 2002. OCTL will also provide an R&D testbed for developing the ground system technologies that would ultimately be used for deep space optical communication applications. It is envisioned that a 1-meter uplink telescope, similar to OCTL but potentially with the addition of adaptive optics for outer solar system missions, would be complemented by a larger, 10-meter class "photon bucket" - a non-diffraction-limited optical collector for receiving the downlink optical signal.

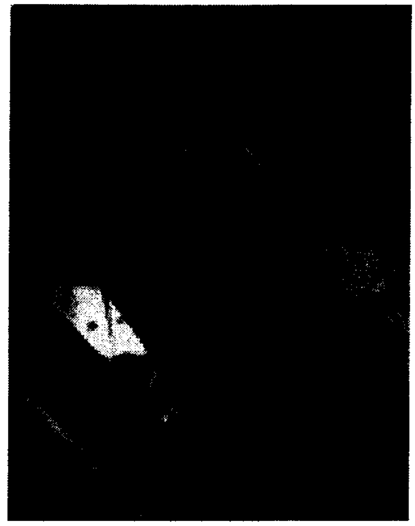

Figure 3: Multi-beam laser uplink from Table Mountain 0.6m Telescope to the ETS-VI spacecraft during the Ground to Orbit Lasercom Demo (GOLD)

Based on current optical communications system design, a single 10m ground station supporting a downlink from a spacecraft at Jupiter equipped with a 3W, 30 cm optical transmitter could roughly the same data rate as the equivalent performance of *all* of the DSN's current X-band antennas arrayed together, receiving a 10W X-band signal from a 1.5-meter spacecraft antenna. And it is expected that future component level improvements in optical detector and laser efficiencies, as well as improved optical modulation and coding schemes, will further increase these performance gains. TMOD's current communications roadmap calls for technology development and demonstrations in the 2000-2005 time frame with OCTL, and the initial deployment of the first operational 10m ground station(s) in the 2008-2010 time frame. Looking beyond 2010, an important strategic decision is whether to continue the relatively low-cost development of optical ground stations, which must contend with significant atmospheric effects, or to move to Earth-orbiting assets to support deep space optical communications. Technology breakthroughs in low-cost spacecraft and lightweight optical system will play a key role in this decision.

In Situ Communications and Navigation

Small planetary landers and rovers will demand highly efficient, low-mass, low-power short-range communications. Constellation and formation flying applications, such as future space interferometer missions with distributed free-flying apertures, are another scenario where short-range communications solutions are required. In many of these cases, missions will benefit from also extracting accurate radio metric observables from these in situ links to achieve precise navigation for high-accuracy landing, rendezvous and docking, and/or precision constellation control.

Several parallel thrusts are underway at JPL in response to these needs. The Micro Communications and Avionics System (MCAS) targets a highly integrated short-range radio incorporating a mixed signal ASICs and MEMS-based oscillators and filters to achieve aggressive mass, power, and volume goals. A second approach, dubbed the Autonomous Formation Flyer, exploits GPS-on-a-chip technology to develop a flexible microprocessor-based chipset that combines precise one-way carrier phase and pseudorange measurements with high-rate telemetry. Each of these approaches are well-suited to specific classes of mission needs.

Protocols, Coding and Data Compression

The long round-trip light times, high bit error rates (compared to terrestrial fiber links), and intermittent link availability encountered in interplanetary communications are incompatible with current Internet Protocol (IP) standards. TMOD is funding the development of new standards which represent a natural evolution of IP functionality to the deep space environment. The CCSDS File Delivery Protocol (CFDP), currently in development, will provide for reliable and robust file delivery from in situ vehicles back to Earth, even through multiple, intermittent relay communications assets.

New classes of error correcting codes, known as Turbo codes, are being developed which will increase data communications rates achievable for a given spacecraft radio system. These codes offer more 2 dB better performance than the standard (7,1/2) convolutional code, and nearly 1 dB better than the newer (15,1/6) code, and the lower decoder complexity allows the use of these codes at higher bit rates. TMOD is planning to implement an operational turbo decoding capability within the DSN by 2003.

In spite of all of these communications-enhancing technologies, for deep space missions we will always be working in a regime in which the available data rates back to Earth are small compared to terrestrial capabilities we take for granted, and compared to the raw data rates of advanced multispectral sensors. Maximizing the *information* that we can convey on this bandwidth-constrained link will require aggressive use of data compression. New lossless and lossy data compression techniques are being developed for use in the Mars Surveyor Program and other deep space missions. Beyond conventional data compression, concepts like progressive transmission and onboard data mining will be used to extract data subsets of highest science value for transmission to Earth.

A Mars Network for Telecommunications and Navigation

Mars represents a near-term target where many of these technologies can come together to establish the first step towards an Interplanetary Internet. NASA has recently completed a comprehensive study of the overall architecture of Mars exploration in the time frame through 2011, including robotic sample return missions, precursor missions for human exploration, and a wide range of low-cost science micromissions. In the context of this study, the enhancing and enabling aspects of a Mars Network, providing increased telecommunications and navigation capabilities, were recognized. Pathfinder-era capabilities of 30 Mb/sol data return and few-hours/sol link connectivity represent a fundamental barrier to increasingly sophisticated Mars in situ exploration. Two conceptual building blocks for an evolving Mars Network were identified during the study. The first is a very low-cost microsatellite, which would be launched as a piggyback payload on a commercial Ariane launch into geosynchronous transfer orbit. The 200-kg microsatellite would then park in an Earth-moon orbit until the optimal time for transfer to Mars. A constellation of these satellites would be established in low altitude (400-1000 km) Mars orbits, providing high-sensitivity UHF relay capabilities, frequent telecommunication contacts, and GPS-like navigation services to surface assets. A constellation of six such satellites could provide multi-Gb/sol data return with dozens of contacts per sol.

The second building block is called the Mars Areostationary Relay Satellite (MARSAT), and would orbit Mars at an altitude of 17,000 km in a circular, equatorial orbit with a period of 1 sol; i.e., the Martian equivalent of a Earth geostationary satellite. Using high-gain links at X-band or Ku-band between the surface and MARSAT, and a 100 W Ka-band link back to Earth, MARSAT would provide nearly continuous 1 Mb/s data rates from the surface of Mars back to Earth, supporting streaming video imagery (or other high data rate information) from in situ spacecraft to scientists and the public on Earth. This quantum leap in bandwidth and connectivity would fundamentally change our science mission operations concepts and open exciting new doors in how NASA can engage the public in the excitement of Mars exploration (Figure 4).

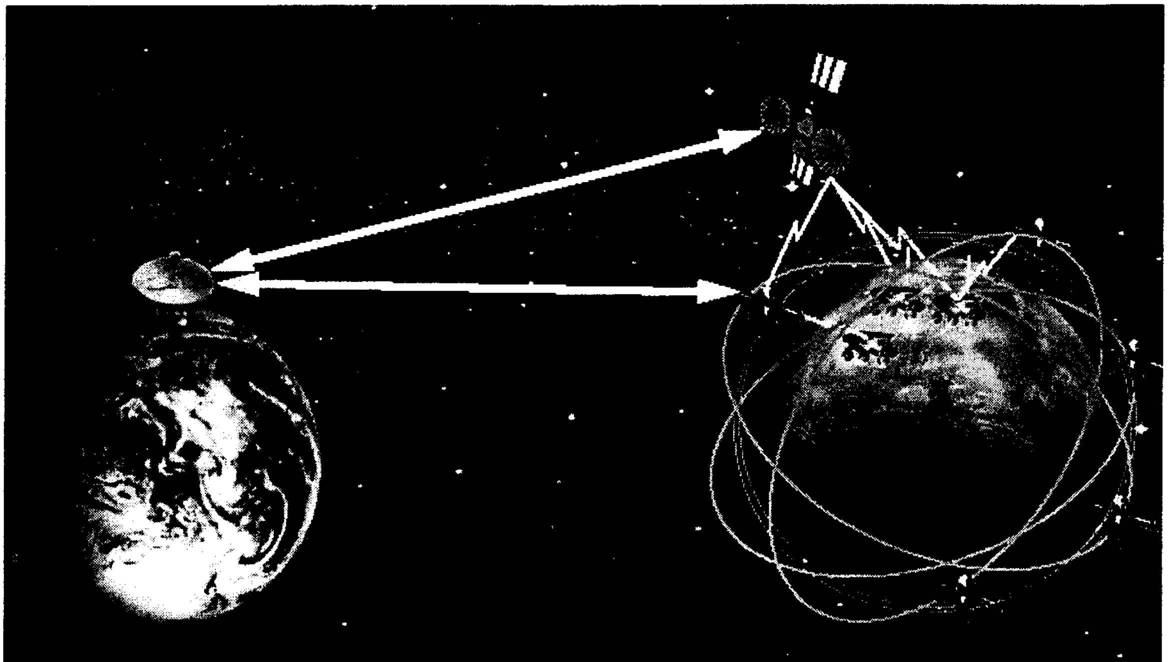

Figure 4: Conceptual view of a Mars Network for providing enhanced and enabling telecommunications and navigation capability for future robotic and human mission to Mars.

Conclusions

The opportunity exists to start the formation of an Interplanetary Internet in which information flows freely across the solar system to connect scientists and the public to NASA's future space missions. In particular, the intensive exploration of Mars in the coming decade will represent the first instance of this Interplanetary Internet. Communications technology advances that support increased data rates over planetary distances, coupled with efficient short-range communications systems, dedicated relay assets, new IP-like protocols, and methods for efficiently moving information across these deep space links, will greatly increase NASA's capability to deliver on its promise of establishing a virtual presence throughout the solar system.

Acknowledgments

The author gratefully acknowledges the contributions of Gael Squibb, Laif Swanson, Peter Shames, Les Deutsch, Jim Lesh, Shel Rosell, Adrian Hooke, and the many technologists working in the TMOD Technology Program at JPL. The work described was performed at the Jet Propulsion Laboratory, California Institute of Technology under contract with the National Aeronautics and Space Administration.